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TITLE OBSERVATIONS AND PREDICTIONS OF EUV EMISSION FROM CLASSICAL NOVAE

AUTHOR(S) Sumner Starrfield, James W. Truran, Warren M. Sparks, Joachim Krautter

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

OBSERVATIONS AND PREDICTIONS OF EUV EMISSION FROM CLASSICAL NOVAE

Sumner Starrfield[1], James W. Truran[2], Warren M. Sparks[3], and Joachim Krautter[4]

ABSTRACT

Theoretical modeling of novae in outburst predicts that they should be active emitters of radiation both in the EUV and soft X-ray wavelengths twice during the outburst. The first time is very early in the outburst when only an all sky survey can detect them. This period lasts only a few hours. They again become bright EUV and soft X-ray emitters late in the outburst when the remnant object becomes very hot and is still luminous. The predictions imply both that a nova can remain very hot for months to years and that the peak temperature at this time strongly depends upon the mass of the white dwarf. It is important to observe novae at these late times because a measurement of both the flux and temperature can provide information about the mass of the white dwarf, the turn-off time scale, and the energy budget of the outburst. We review the existing observations of novae in late stages of their outburst and present some newly obtained data for GQ Mus 1983 We then provide results of new hydrodynamic simulations of novae in outburst and compare the predictions to the observations.

[1]Department of Physics and Astronomy, Arizona State University and Theoretical Division, Los Alamos National Laboratory

[2]Department of Astronomy, University of Illinois

[3]Applied Theoretical Physics Division, Los Alamos National Laboratory

[4]Landessternwarte Heidelberg Königstuhl

I. INTRODUCTION

Over the past two decades, observational studies have revealed and theoretical studies have predicted that classical novae, over the course of their outbursts, emit energy over a broad range of wavelengths, from radio to gamma-ray. While the theoretical predictions of novae outbursts have anticipated some of the observations, in this paper we identify a number of phenomena that show that current predictions are not totally in agreement with the observations.

The classical nova outburst occurs on the white dwarf component of a close binary system and they are members of the general class of Cataclysmic Variables. A Cataclysmic Variable (hereafter: CV) is commonly assumed to contain a Roche Lobe filling secondary, on or near the main sequence, losing hydrogen-rich material through the inner Lagrangian point into an accretion disk that surrounds a white dwarf primary. Some viscous process, as yet unknown, acts to transfer mass inward and angular momentum outward through the disk so that some fraction of the material lost by the secondary ends up on the white dwarf. The accreted layer slowly grows in thickness until the bottom reaches a temperature that is high enough to initiate thermonuclear burning of hydrogen. The further evolution of nuclear burning on the white dwarf now depends upon the mass and luminosity of the white dwarf, the rate of mass accretion, and the chemical composition of the reacting layer.

Given the proper conditions, a thermonuclear runaway (hereafter: TNR) occurs, and the temperatures in the accreted envelope grow to values exceeding 10^8K. At this time the β^+-unstable nuclei become abundant which strongly affects the further evolution of the outburst. Theoretical calculations demonstrate that this evolution releases enough energy to eject material with expansion velocities that agree with observed values and that the predicted light curves produced by the expanding material can agree quite closely with the observations (Sparks, Starrfield, and Truran 1978; Starrfield, Truran, and Sparks 1978; Starrfield, Sparks, and Truran 1974a, 1974b, 1985, 1986; Prialnik, Shara, and Shaviv 1978, 1979; MacDonald 1980; Prialnik *et al.* 1982). These studies have also been extremely successful in reproducing the gross features of the nova outburst: ejected masses and kinetic energies.

More importantly, these calculations predicted: (1) that enhanced CNO nuclei would be found in the ejecta of fast novae, (2) that the isotopic ratios of the CNO nuclei would be far from solar, and (3) that there should be a post maximum phase of constant luminosity lasting for months, or longer. As discussed in Starrfield (1986, 1988), observational confirmation of each of these points has now appeared in the literature.

Given this brief discussion of the outburst, we can identify the various times during the outburst when a nova will be expected to emit radiation at EUV and soft X-ray wavelengths. The physical causes underlying these emissions are well known and well understood; it is the calculation of emission at various wavelengths and times that has not previously been done.

In the next section we present a summary of the existing simulations of the nova outburst. We follow that with Section III, which shows how the early EUV emission may be estimated, and Section IV, which shows how the late EUV emission may be determined. That section also discusses the current situation with regards to radiation pressure driven mass loss. In Section IV we review the existing observations that show that novae are already known to be EUV and soft X-ray emitters. We end with a discussion and conclusions.

II. THEORETICAL SIMULATIONS OF THE OUTBURST

Significant advances in our understanding of the outbursts of classical novae have occurred over the past decade (see, e.g., the reviews Gallagher and Starrfield 1978; Truran 1982; Starrfield 1988; Shara 1988). Their outbursts are now understood to be driven by TNR's proceeding in the accreted hydrogen rich shells on the white dwarf components of close binary systems. The varied characteristics of the observed outbursts can be understood on the basis of dependencies on the white dwarf mass and luminosity, the rate of mass accretion, and the composition of the envelope matter prior to runaway. Observations of novae ejecta imply that there is mixing of core material into the accreted layer so that the observed chemical composition of the ejecta reflects a combination of core plus accreted material (Sparks *et al.* 1988).

The outburst proceeds as follows. If the material is degenerate enough, a TNR occurs, and the temperatures in the accreted envelope grow to values exceeding 10^8K. At temperatures of 10^8K and above, the β^+-unstable nuclei become abundant and *important*. It is the operation of the CNO reactions at high temperatures and densities that produces large amounts of the β^+-unstable nuclei in the envelope and one of the most important results from the hydrodynamic simulations has been the identification of the role played by the β^+-unstable nuclei in the outburst.

The four nuclei: ^{13}N, ^{14}O, ^{15}O, and ^{17}F influence the outburst in the following fashion: during the early part of the evolution, the lifetimes of the CNO nuclei against proton captures are very much longer than the decay times for the β^+-unstable nuclei [$\tau(^{13}N) = 863s$, $\tau(^{14}O) = 102s$, $\tau(^{15}O) = 176s$, $\tau(^{17}F) = 92s$] so that these nuclei can decay and their daughters capture another proton in order to keep these reactions cycling. As the temperature increases in the shell source, the lifetime against proton capture continually decreases until, at temperatures of $\sim 10^8$K, it competes favorably with the β^+ decays. The abundances of these nuclei now increase to where they severely impact the nuclear energy generation in the envelope since every proton capture must now be followed by a waiting period before the β^+ decay occurs and another proton capture can occur. Thus the energy generation loses its dependance upon temperature and density and is completely controlled by the CNO abundances.

We also note that all of the computer simulations show that during the evolution to peak temperature a convective region forms just above the shell source and then grows to include virtually the entire accreted envelope. Since the convective turn-over time scale in the envelope is $\sim 10^2$ sec near the peak of the TNR, a significant fraction of the β^+-unstable nuclei can reach the surface without decaying and the rate of energy generation at the surface can exceed 10^{12}-10^{13} erg gm^{-1}s^{-1} (Starrfield, Truran, and Sparks 1978; Starrfield 1989). Thereafter, the energy produced in the shell source rapidly reaches the surface and we find that the radiative luminosity climbs to maximum on the convective turn-over time scale at a time when the white dwarf radius is still small. Clearly, an object radiating with luminosities $\sim L_{Ed}$, and which has a radius of a few times 10^8cm, will emit copious amounts of EUV and soft X-ray photons. This implies that the nova will be bright in the EUV or soft X-rays hours or days before optical maximum depending upon the speed class of the nova. Figure 1 shows the evolution in time of the T_e for one hydrodynamic model.

III. THE EARLY EUV EMISSION OF A NOVA

Given the picture of the nova outburst as outlined in the previous section, it becomes possible to provide an estimate of the peak T_e, which occurs early in the outburst, as a function of white dwarf mass. In this section we are concerned only with the very beginnings of the outburst when the luminosity of the nova is rising to bolometric maximum and long before it reaches visual maximum. To our knowledge no nova has been observed at this time in its outburst.

In order to proceed, we assume that the dynamical time scale of the envelope is such that the white dwarf can reach peak luminosity at a time when its radius is still small. This assumption is confirmed by all of the hydrodynamic calculations which show that the β^+-unstable nuclei reach the surface at a time when the envelope has not yet begun to expand. The theoretical calculations also show that for fast novae the luminosity can exceed the Eddington luminosity at the surface. If we assume that the radius remains constant during the rise to bolometric maximum, then we can estimate the peak T_e during the explosion.

We proceed by calculating the radius of a white dwarf as a function of mass (Figure 2; Eggleton 1982). We then assume that the nova reaches the Eddington luminosity and use the standard expression, for L_{Ed} as a function of mass (assuming a solar mixture of elements), to obtain a predicted temperature. This is shown in Figure 3. It is clear that even under the simplest assumptions one can expect a nova at maximum to be a strong EUV and soft X-ray emitter. In addition, the observed effective temperature will be a strong function of the white dwarf mass.

Moreover, we have also done a number of calculations of TNR's on white dwarfs of different masses and chemical compositions and tabulated the peak T_e. The results of unpublished work at $1.00M_\odot$ and $1.25M_\odot$ (Starrfield, Truran, and Sparks 1989; in preparation) and published work at $1.25M_\odot$ (Starrfield, Sparks, and Truran 1986), $1.35M_\odot$ (Starrfield, Sparks, and Shaviv 1988) and $1.38M_\odot$ (Starrfield, Sparks, and Truran 1985) are also shown in Figure 3. At each mass we show an average of the peak effective temperatures found in these calculations. The peak temperatures in the simulations are significantly lower than predicted by the simple relationship. The explanation is that radius expansion has occurred and in some cases the radius of the star has increased by more than 10 per cent with a concomitant reduction in peak T_e. However, the general slope is similar and does support the conclusions stated in the previous paragraph.

Unfortunately, this stage of evolution is very short and could be over in as little time as one hour. It is possible that such an outburst could be detected in a very sensitive all sky survey at either EUV or soft X-ray wavelengths and would appear as a very soft transient outburst. We encourage the observers to be alert to such a possibility.

IV. THE POST MAXIMUM EUV EMISSION FROM NOVAE IN OUTBURST

After the expansion and dispersal of the ejected layers, the hydrodynamic simulations predict and observations confirm that there is a phase of constant luminosity (Sparks, Starrfield, and Truran 1976) for all novae which occurs because only a fraction of the accreted envelope is ejected during the initial explosion. The remaining material (anywhere from 10% to 90%) quickly returns to quasistatic equilibrium with a radius extending to $\sim 10^{11}$cm to 10^{12}cm. Because the shell source is still burning at the bottom of the envelope, the luminosity can be determined from the core mass-luminosity relationship which predicts that the luminosity of the remnant depends only on the mass of the white dwarf (see Iben 1982 and references therein). For a massive white dwarf that value of the luminosity is close to $\sim L_{Ed}$. Therefore, as mass is lost, the effective temperature will grow to exceed a few times 10^5K producing a second phase of EUV or soft X-ray emission. We address that phase in this section. We also note that material ejected during the nova outburst has velocities exceeding 10^3km s $^{-1}$. This high a velocity is enough to produce X-rays from shocks produced by the expanding material running into any circumbinary material (Brecher, Ingham, and Morrison 1977; Bode and Kahn 1985; Mason *et al.* 1986).

A critical point, which has yet to be understood, concerns the question of the time scale of the constant luminosity phase; i.e., how long does it take for the cessation of nuclear burning and the ensuing return of the nova to its quiescent state. The observations have confirmed that this phase of evolution proceeds more rapidly than the nuclear burning time scale for the remnant hydrogen envelope. This implies that some mechanisms must be at work to remove the remnant envelope and turn off the outburst. Whatever these mechanisms are, we can expect that the radius will shrink with time and the size of the star will slowly return to that expected for a white dwarf. This phase, however, will occur at nearly constant luminosity and so the effective temperature will slowly increase. As shown by the observations of most novae, and especially by those of GQ Mus (Krautter and Williams 1989), T_e can reach values exceeding 5×10^5K.

Discussions of the mechanisms and time scales for turn-off can be found in Starrfield (1979) and MacDonald, Fujimoto, and Truran (1985). In addition, it is also appropriate to point out that Shara *et al.* (1977) realized quite early that novae that erupted with insufficient envelope mass would be unable to reach a radius exceeding 10^{11}cm and that an EUV outburst would be the only indication of the TNR. Similar evolutionary behavior for recurrent novae was found by Truran *et al.* (1988). Here, however, we are concerned with the turn-off of a nova that has experienced an optical outburst.

In the rest of this section, we assume that it is a stellar wind that is acting to drive mass off the remnant at a rate that can be calculated by the expressions provided by the theory of radiation pressure driven winds (Castor, Abbot, and Klein 1975; Abbot 1982; and references therein). We use their formulae as written in MacDonald, Fujimoto, and Truran (1985) in order to derive a mass loss rate as a function of white dwarf mass. In addition, we assume that the white dwarf is radiating at the plateau luminosity of Iben (1982: although any of the tabulated core mass-luminosity relations give virtually the same answer), a solar mixture of the elements, and that the radiation driven mass loss expressions are valid up to temperatures of 10^6K. It is this last assumption that is most questionable but we only use this expression to obtain an estimate of the time scales for turn-off and use the actual observations to constrain our calculations. Figure 4 shows the rate of mass loss as a function of white dwarf mass. The increase in the rate, as we go to higher masses, is striking and shows that a determination of the turn-off time scale could also be used to estimate the white dwarf mass. It is also clear that radiation pressure driven mass loss can be solely responsible for the turn-off of a nova after maximum and our initial assumption was correct.

In order to estimate the time scale for turn-off and thus the amount of time that we will have available to observe a nova in the late EUV stage of the outburst, we use the expression given in

Starrfield (1989) to estimate the envelope mass (see also Truran and Livio 1986) at the time of runaway and assume that a fraction of this material is left on the white dwarf after the explosive phase of the outburst. The numerical simulations show that this fraction can vary from 10% to 90% and that it is a function of the degree of enhancement of the CNONeMg elements. For the purpose of this exercise, we assume 50%. Given the remnant envelope mass, we then use the rate of mass loss to estimate the time for a white dwarf of a given mass to eject its remaining envelope. That time is shown in Figure 5 as a function of white dwarf mass. Clearly, for the most massive white dwarfs, the times are too short to agree with the observations.

The reason for this discrepancy is that the radiation pressure driven mass loss theory depends upon the interaction of photons from the central source with absorbers in the envelope. At temperatures exceeding 5 x 10^5K, most of the material is fully ionized and the absorption will be very small. It would seem reasonable that the efficiency of the interaction could be 10 per cent or less of the values determined for stellar material at temperatures below 5 x 10^4K. Therefore, we feel that the actual rates of mass loss could be more than 10 times smaller then shown in Figure 5. This would bring the time scales shown in Figure 5 in line with the observations.

Given the discussion in this section, the nova evolves at a constant luminosity, but steadily increasing T_e, until the amount of mass remaining on the star is too small to support further nuclear burning. The remnant material, if any, will then collapse back onto the surface of the star on a time scale of weeks and will go through a phase where the temperature reaches to nearly the theoretical value shown in Figure 3. The time for this phase is the Kelvin-Helmholtz time for the material in the envelope and is very short.

V. OBSERVATIONS OF NOVAE

Three recent reviews of the UV studies of novae (done mainly with the IUE Satellite) have recently appeared (Starrfield and Snijders 1987; Starrfield 1987; Starrfield 1988). A large number of novae have now been studied in the UV and those data have proved to be very important in our understanding of the outburst. They show that as the outburst progresses both that the luminosity remains virtually constant (Wu and Kester 1977) and also that the peak in the energy distribution shifts toward shorter wavelengths. No nova has been found early enough in its outburst to be detected in the early EUV phase and only two novae have been studied for a long enough time in their outburst to detect a late EUV phase. One of these is GQ Mus 1983 and in Figure 6 we show a de-reddened spectrum obtained by the IUE satellite on January 15, 1988. It is clear from the continuum, sloping to the blue, that this star is very hot. Optical spectra obtained for this novae in 1987 and 1988 also indicate that a hot source exists within the expanding shell (Krautter and Williams 1989). Krautter and Williams (1989) find FeX stronger than Hα as well as other indications that a photoionizing source with a temperature exceeding $\sim 5 \times 10^5$K is present in the system. They also report that this source must still be luminous. The other nova is QU Vul 1984 and UV spectra obtained in June 1988 and December 1988 show only emission lines.

A recent review of the X-ray studies of novae can be found in Starrfield (1988). In spite of attempts by **Einstein** (Becker and Marshall 1981), novae were not detected in outburst at X-ray wavelengths until **Exosat** observed emission from GQ Mus 1983 (Ögelman, Beuermann, and Krautter 1984). This was followed shortly thereafter by **Exosat** observations of X-rays from Nova PW Vul 1984 and QU Vul 1984 (Ögelman, Krautter, and Beuermann 1987). In addition, RS Oph, a recurrent nova, was also detected by **Exosat** (Mason *et al.* 1986). The observations implied that all three novae had $T_e \sim 3 \times 10^5$K and a luminosity that corresponded to a $1.0M_\odot$ white dwarf radiating at $\sim L_{Ed}$ (Ögelman, Krautter, and Beuermann 1987). Nevertheless, as emphasized by Ögelman, Beuermann, and Krautter (1984) and Ögelman, Krautter, and Beuermann (1987), the data were not consistent with the predictions of the TNR theory which required much higher temperatures at late stages in the outburst. The temperatures found above are more consistent with low mass (large radius) white dwarfs than with the high mass white dwarfs found to be necessary for a degenerate TNR (Starrfield, Truran, and Sparks 1978; Starrfield 1979; MacDonald, Truran, and Fujimoto 1985).

In addition to the discussion in the previous section, we note that the calculations of Starrfield, Sparks, and Truran (1985) show that T_e should reach much higher values at very late stages in the outburst. However, recent optical spectra suggest that the central source of GQ Muscae 1983 has continued to increase in temperature (Krautter and Williams 1989) which indicates that the radius of the shell is still decreasing.

Ögelman, Krautter, and Beuermann (1987) may have also measured the turn-off time scale for GQ Mus 1983 since their last observation, 900 days after maximum light, suggests that its X-ray flux had decreased by more than a factor of two.

VI. SUMMARY AND DISCUSSION

In this paper we have provided estimates of the EUV emission at two times in the outburst. The first phase occurs very early in the outburst when the energy from the shell source has just penetrated the surface layers and the luminosity reaches L_{Ed} at a time when the radius is still small. There is, as yet, no observational confirmation of this phase. However, we have provided estimates of the maximum temperature that can be reached as a function of white dwarf mass. These estimates come from both an order-of-magnitude calculation and from actual hydrodynamic simulations of the outburst.

The second phase of EUV emission occurs at a late time in the outburst when the radius of the remnant object has shrunk to a few white dwarf radii but the luminosity still remains at nearly the maximum value. We have provided estimates of the time scales for this phase of the outburst as a function of white dwarf mass. We cannot predict the temperatures during this phase since they will depend on the radius of the material remaining on the white dwarf. Nevertheless, they should approach those temperatures derived in the earliest phases of the outburst.

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CAPTIONS FOR FIGURES

Figure 1. The effective temperature as a function of time for a $1.25M_{\odot}$ white dwarf model that is accreting at a rate of $1.0 \times 10^{-8} M_{\odot} yr^{-1}$. It remains at peak T_e for less than one hour.

Figure 2. The radius of a white dwarf as a function of mass. We use the Eggleton (1983) fitting formula to the Chandrasekhar white dwarf mass radius relation.

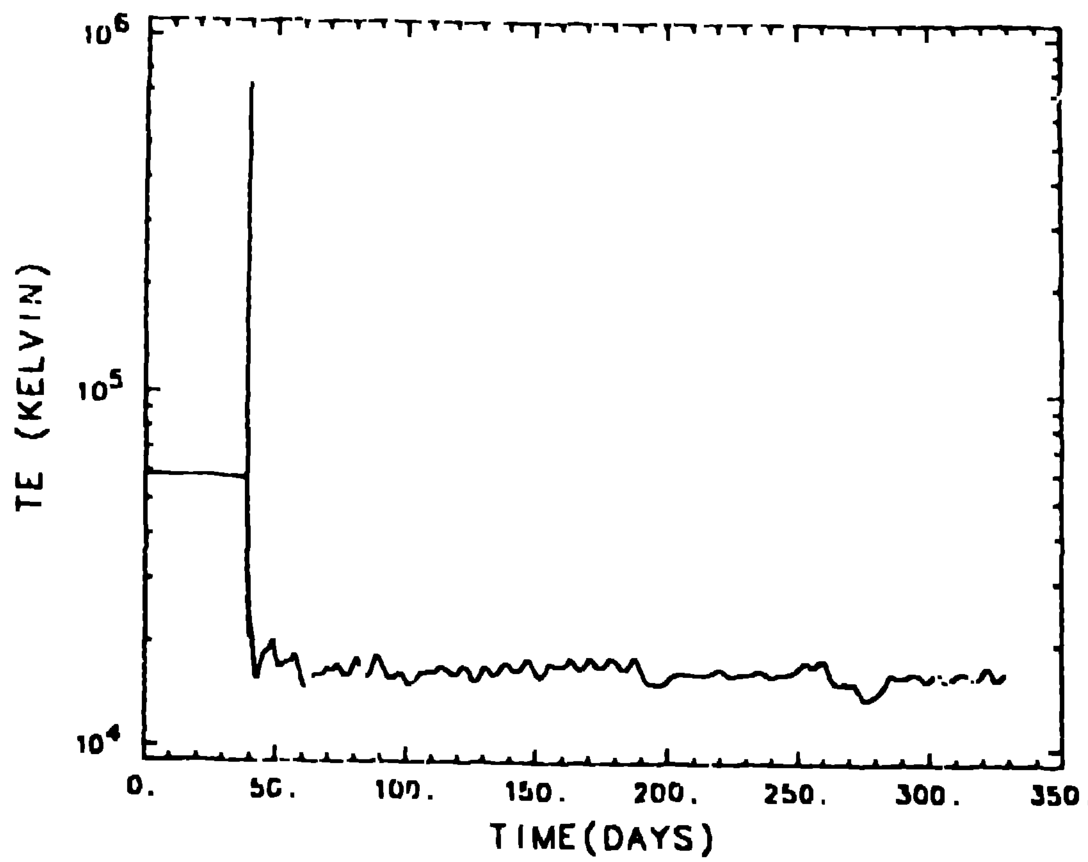
Figure 3. Peak effective temperature for a white dwarf as a function of white dwarf mass. The four asterisks are the results from actual evolutionary sequences at $1.0M_{\odot}$, $1.25M_{\odot}$, $1.35M_{\odot}$, and $1.38M_{\odot}$. The simulated points fall below the derived curve because of envelope expansion prior to the peak of the TNR.

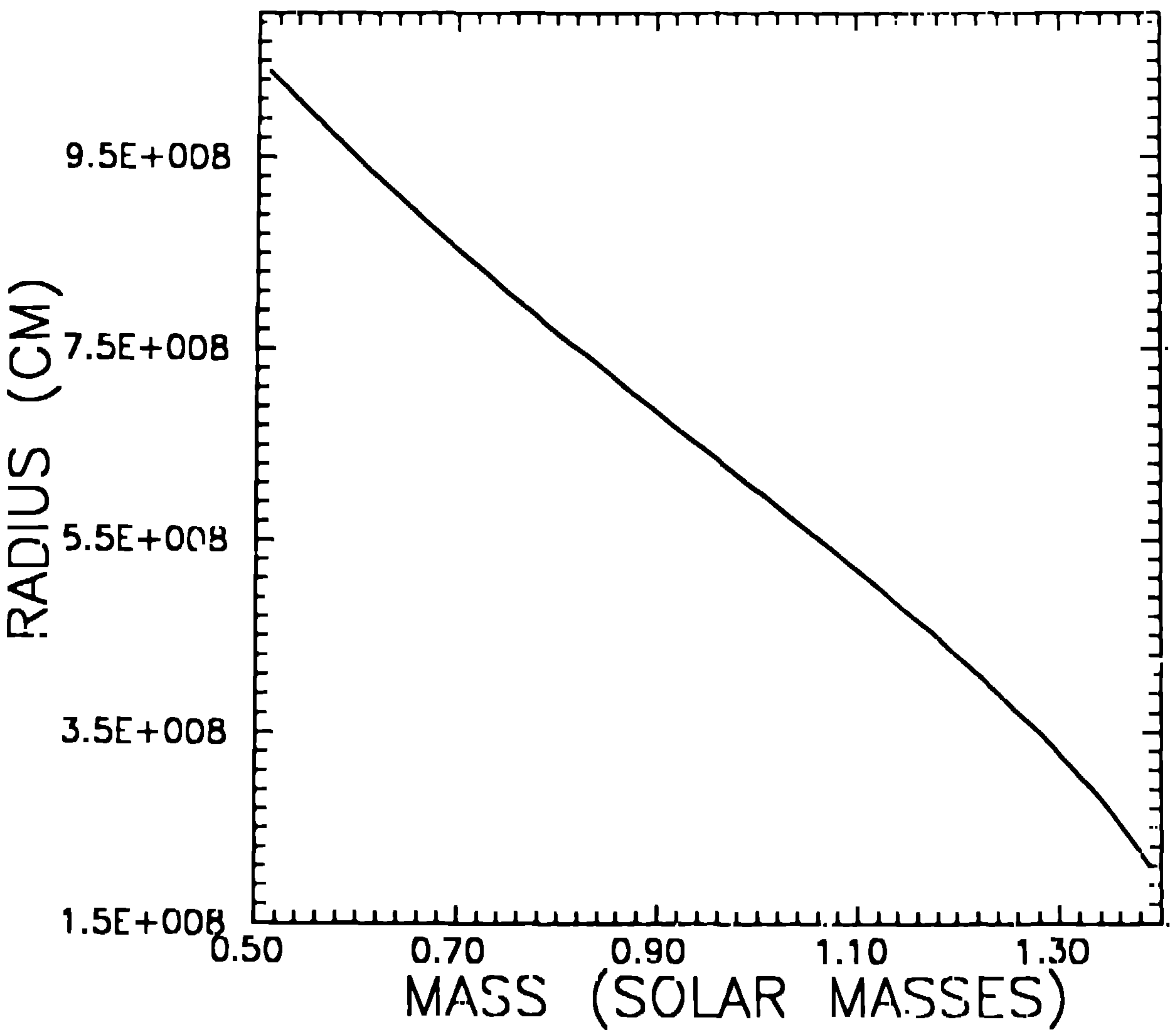
Figure 4. The rate of mass loss in $M_{\odot} yr^{-1}$ as a function of white dwarf mass. This rate is obtained from the radiation pressure driven mass loss theory of Castor, Abbott, and Klein (1975).

Figure 5. The turn-off time scale versus white dwarf mass for a white dwarf radiating at the plateau luminosity (Iben 1982) with an envelope mass determined from standard white dwarf theory. The rapid decrease at large white dwarf masses is caused both by an increasing rate of mass loss and a shrinking envelope mass.

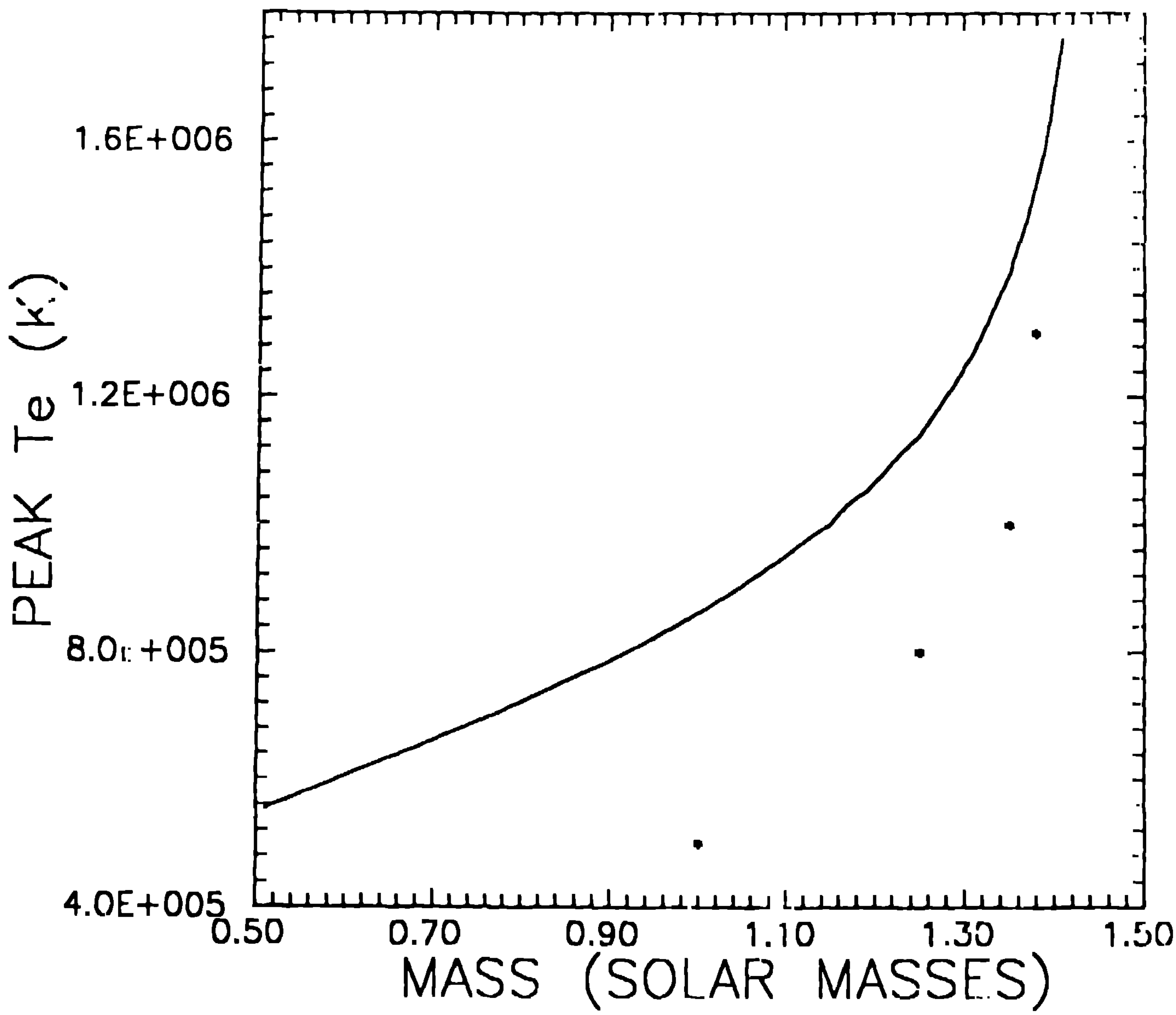
Figure 6. The IUE spectrum of GQ Mus 1983 obtained on January 15, 1988. A spectrum obtained in June 1988 shows virtually the same fluxes and indicates that we are observing the actual stellar continuum. The steep rise of the continuum to the blue suggests that the stellar remnant is very hot.

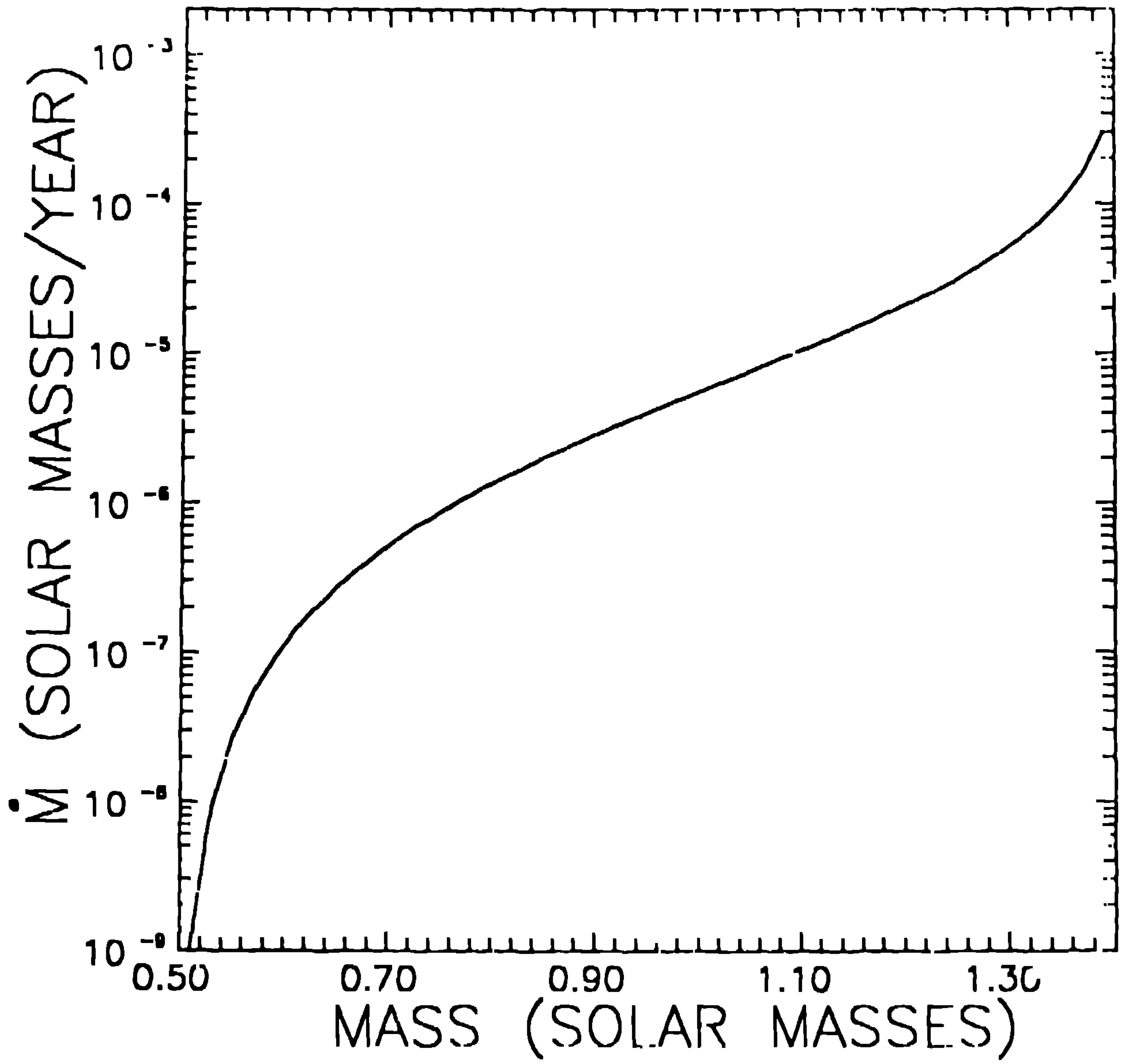
EFFECTIVE TEMPERATURE VS. TIME
ACCRETE O+ 1.25MS L=1.E-2 MDOT=5.0E17
ZONE WHERE TAU=2/3



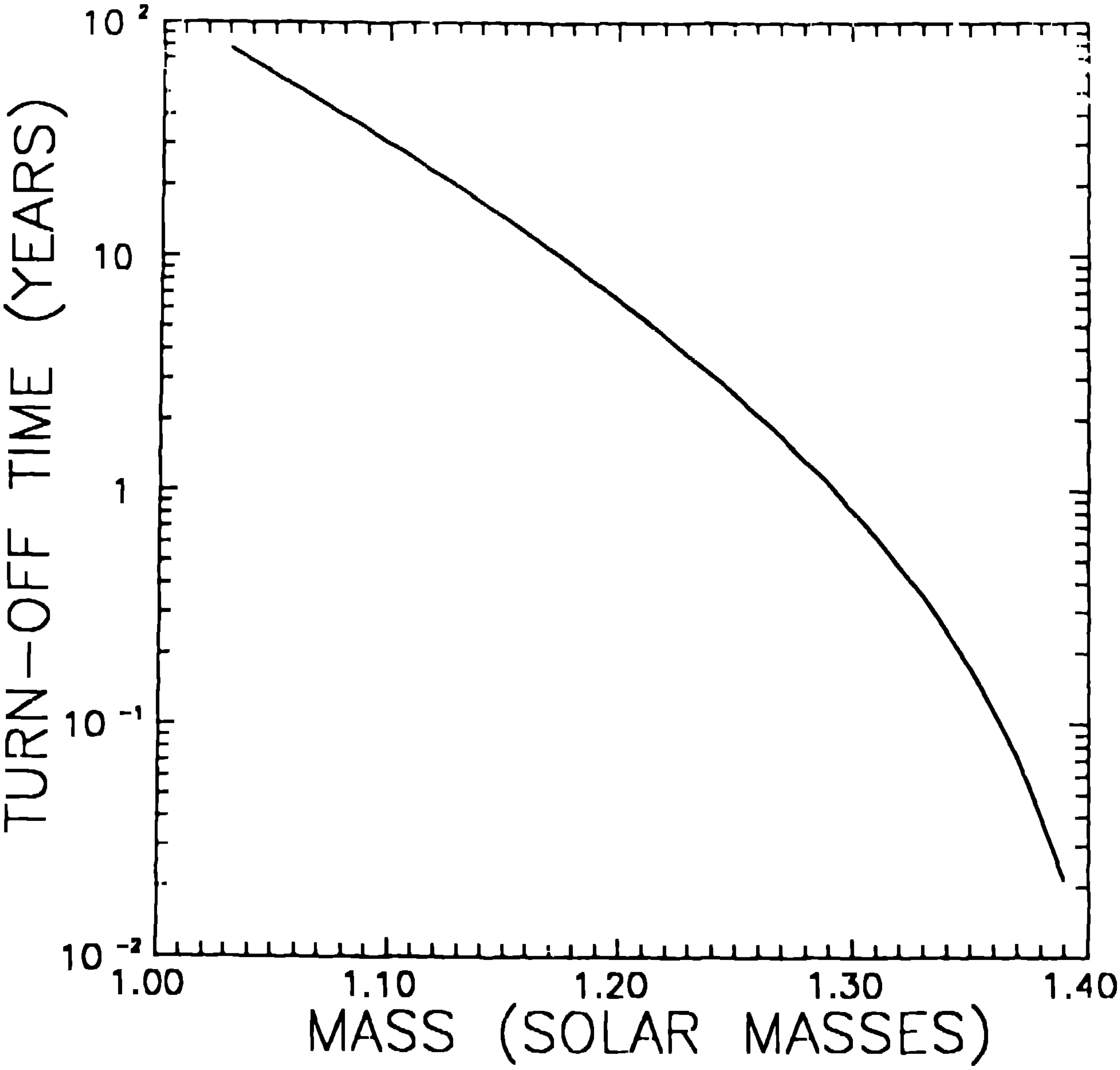


RADIUS (CM)
9.5E+008
7.5E+008
5.5E+008
3.5E+008
1.5E+008
0.50
0.70
0.90
1.10
1.30
MASS (SOLAR MASSES)

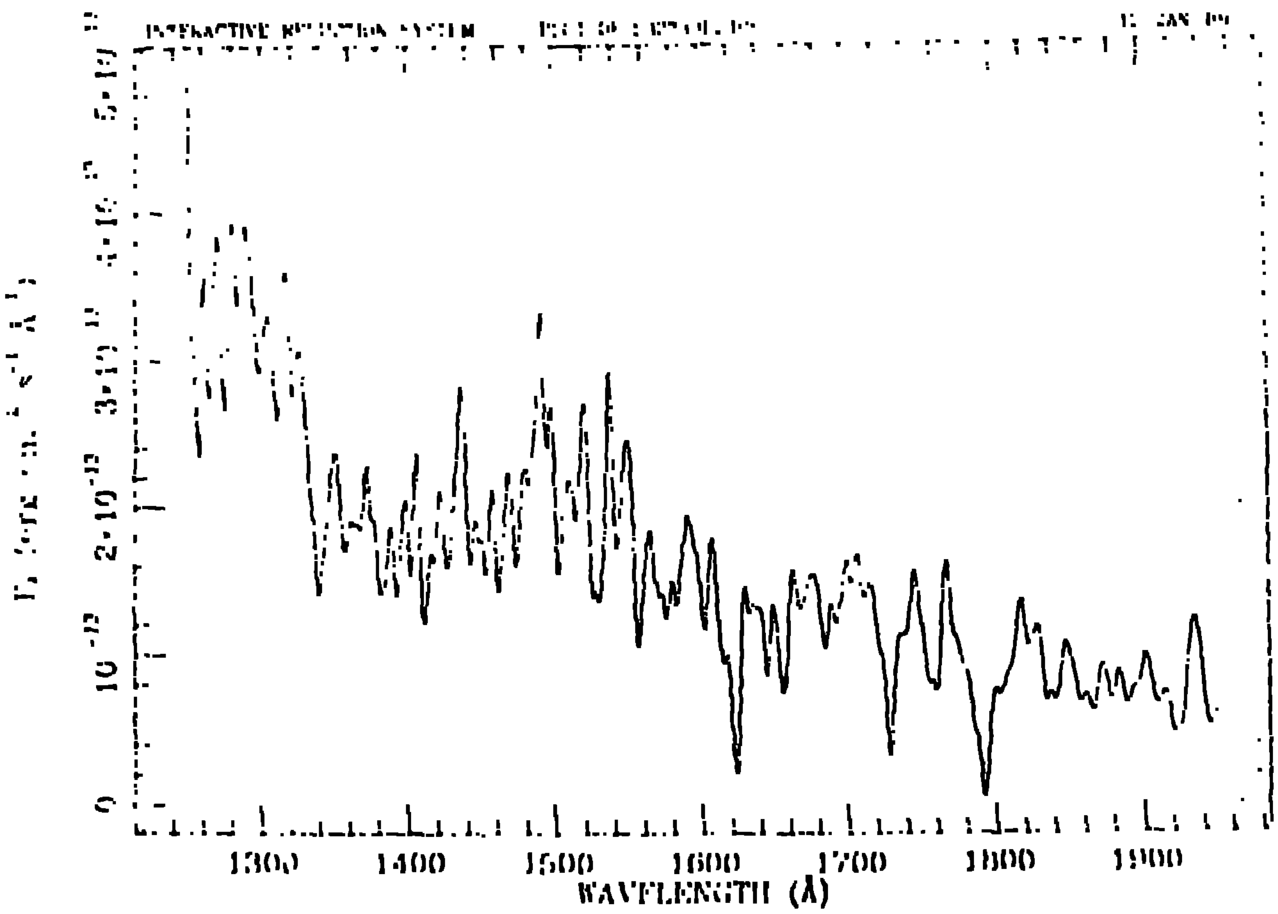

1.6E+006
1.2E+006
8.0E+005
4.0E+005
PEAK Te (K)
0.50
0.70
0.90
1.10
1.30
1.50
MASS (SOLAR MASSES)



$\dot{M}$ (SOLAR MASSES/YEAR)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0.50
0.70
0.90
1.10
1.30
MASS (SOLAR MASSES)



10^{2}
10
1
10^{-1}
10^{-2}
TURN-OFF TIME (YEARS)
1.00
1.10
1.20
1.30
1.40
MASS (SOLAR MASSES)


1300
1400
1500
1600
1700
1800
1900
WAVELENGTH (Å)